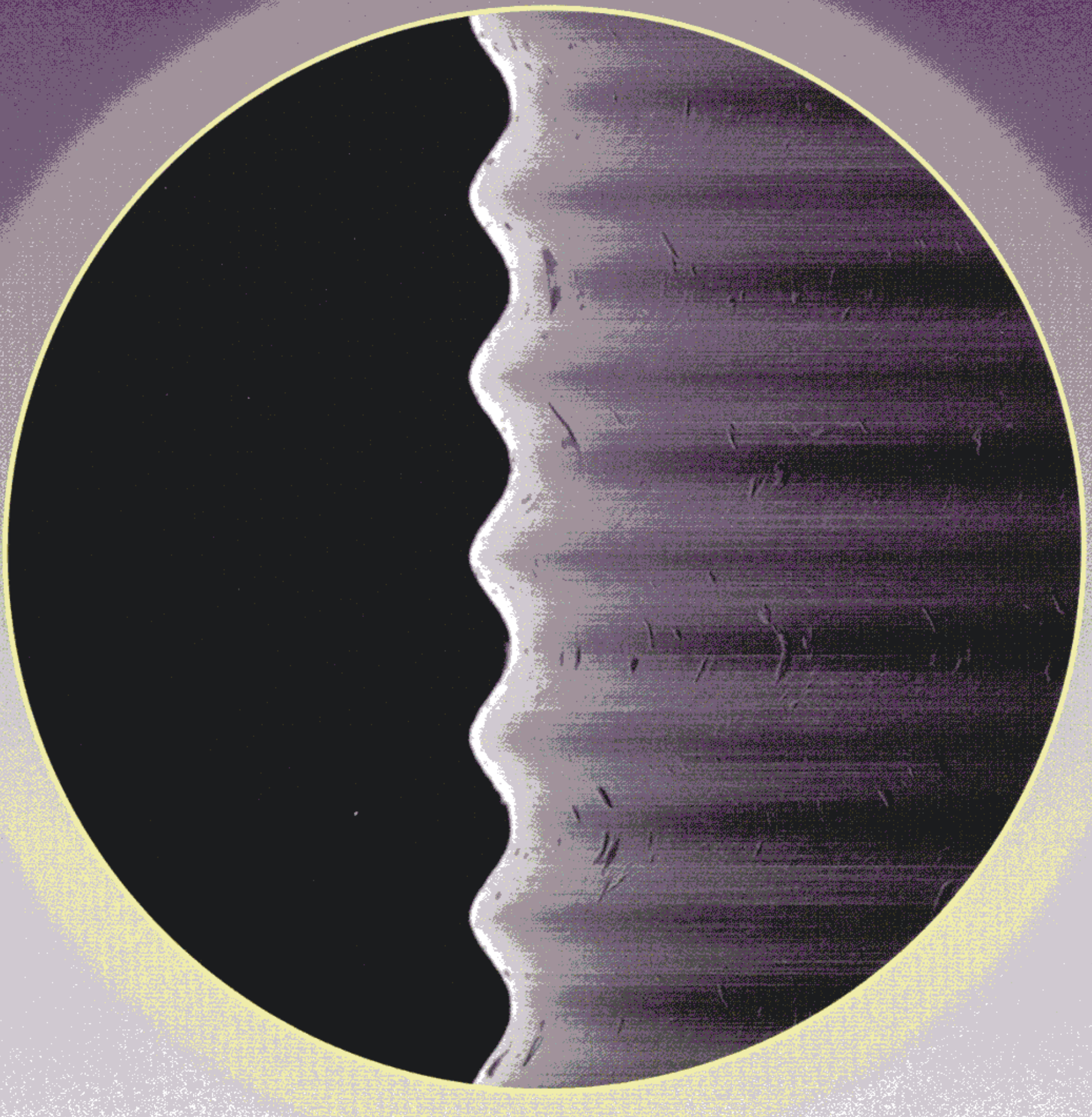
nuclear weapons journal



Winter 2004

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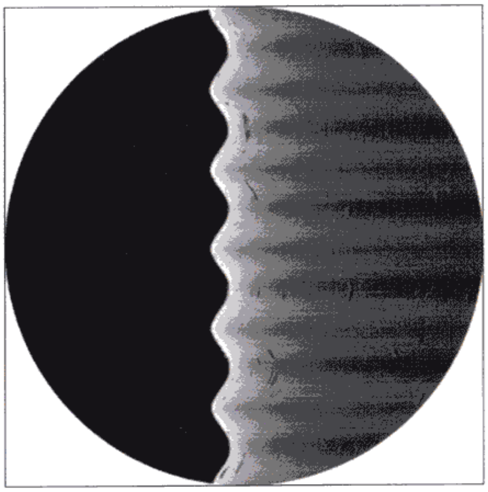

About the cover: Scanning electron micrograph (SEM) of the unstable interface in a Richtmyer-Meshkov hydrodynamic experiment performed using the OMEGA laser, showing a portion of the cylindrical target before the experiment. The laser strikes a layer of epoxy left of the figure and drives a strong shock into the cylinder, causing an implosion and initiating instability at this interface.The sinusoidal perturbations, machined into a thin aluminum layer, have a wavelength of 9 μm and peak-to-peak amplitude of 2 μm. *SEM courtesy of Norm Elliott, MST-7.*

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Correction: The "Backward Glance" in the September/October 2003 issue stated that George Gamov remained a Russian citizen after he fled the Soviet Union in 1933. In fact, he and his wife Rho (Luybov Vokhminzeva) became naturalized American citizens as soon as possible. They were proud of their American citizenship and traveled widely with their American passports. Only under Soviet law and in that territory did they remain Russian citizens. (We thank George's son, Igor, and his wife Elfriede for this information.)

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Validation Experiments in Support of the Nuclear Weapons Stockpile

Experiments to validate physics models are the fundamental testing ground for science-based prediction, the Laboratory's first goal for national security. These experiments are essential to the Laboratory's mission of stockpile stewardship because they provide data needed to test and improve models, algorithms, and computational methods in large-scale simulation codes. These codes are used in the annual assessment and certification of the nuclear stockpile and to address significant findings (problems that require further investigation), as needed. Apparent improvements in simulation codes, achieved with more powerful computers and new and improved models, must be evaluated scientifically to determine their applicability to stockpile stewardship requirements. For example, the fluid dynamics algorithm in a hydrodynamics code must track the progression of fluid flow from an unstable but deterministic flow, through a more complex flow with both deterministic and stochastic components, and subsequently through transition into turbulence. High-resolution model-testing data must challenge the code over a wide range of spatial scales and as a function of time (Figure 1). Experimenters must develop relevant diagnostic techniques and acquire data that will help code developers and designers determine model validity and the limitations of the code that uses the model.

Figure 1. When a planar shock wave impacts three gas cylinders, it creates the three vortex pairs, seen in cross section, by illumination with a thin sheet of laser light. These successive snapshots of the vortex pairs at an earlier time (left) and later time (right) show how the flows become highly distorted en route to turbulence.

Gas Shock-Tube Experiment

The gas shock tube is an excellent example of a validation experiment that is used to investigate fluid dynamics relevant to weapons physics by investigating fluid instability at interfaces between fluids of different densities as they mix and become turbulent after impact by a shock wave (Figure 2). A gun-like apparatus launches a shock wave that becomes planar before accelerating one or more gas columns. Each column is made of slowly flowing sulfur hexafluoride, a heavy, nontoxic gas that serves as the target. The interface between the sulfur hexafluoride and surrounding air becomes unstable and distorts rapidly as the gases mix and become turbulent. Such instability growth, known as Richtmyer-Meshkov Instability, is a weapons physics issue known since the Manhattan Project. Today's experimental techniques and modeling capabilities provide better quantification of the instability process, so our goal is to demonstrate the predictive capability of such flows that occur in weapons.

Current experimental techniques include the flow system that creates the sulfur hexafluoride column, laser-sheet illumination of the post-shock flow, velocimetry based on particle tracking, and high spatial resolution (using large image chips) that is comparable with computed images. The application of particle image velocimetry (PIV) is an especially important advance in our fluid-instability studies. PIV is a diagnostic method used extensively with low-velocity flows, but it is rarely used with flows accelerated by shock wave. The technique involves adding microscopic tracer fog particles to the flow and illuminating the traced flow with a thin sheet of light to photograph a cross section of the flow. Two photographs taken stroboscopically in rapid succession produce a double exposure with observable discrete particles. Using a correlation-based analysis of tracer-particle clusters, we map the flow during the time between exposures. Using the measured time interval between photos, we determine the velocity vector of each particle cluster and thereby produce a two-dimensional (2-D) map of the velocity field for a Mach 1.2 flow.

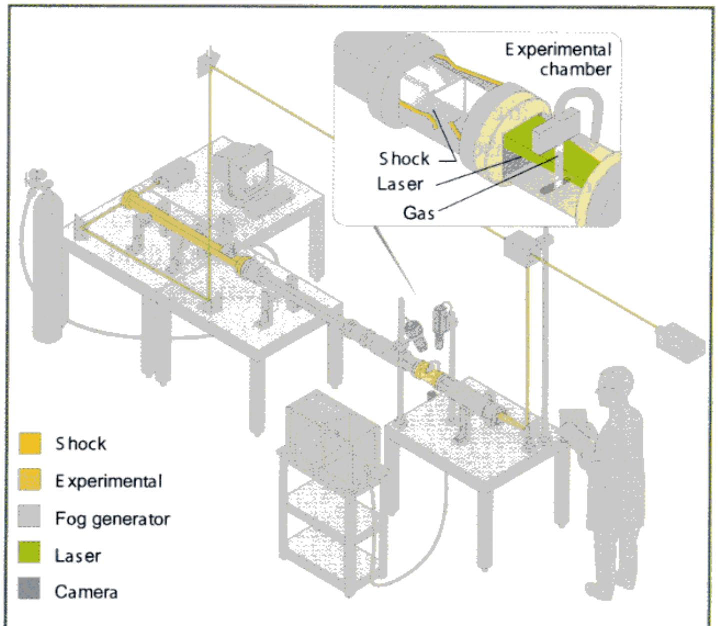

Figure 2. The shock-tube apparatus consists of a long, gun-like tube to produce the shock wave; a laser and cameras to measure the flow; and gas-handling equipment to prepare the gas targets.

This velocity-field measurement significantly enhances the value of the experiment for validation because testing a velocity field calculated by fluid simulation is a more sensitive evaluation of fluid dynamics modeling than comparing only the experimental and simulated density fields. Figure 3 compares measured and simulated velocity fields and vorticity fields that capture the flow swirl. Note that the simulation accurately calculates the velocity field at large spatial scales (several millimeters), but fails to calculate the experimentally observed submillimeter structure, the microvortices. Consequently, this validation experiment has been used to determine a code limitation; improved modeling ensures the needed improvements.

Planar laser-induced fluorescence (PLIF) is yet another experimental validation technique. Using a fluorescent vapor to trace the flow, PLIF dramatically increases spatial resolution, as seen in the PLIF images of three heavy-gas cylinders accelerated by a planar shock wave (Figure 1). These experiments with PLIF have demonstrated science-based prediction by revealing a subtle effect in the two-cylinder experiments that was predicted theoretically but was not detected earlier with fog-traced flow.

Shock-Tube Analysis Methods and Data Interpretation

Advanced analysis methods are being developed to quantify the comparison between high-resolution data and simulation results. We are moving beyond the "viewgraph norm" that involves subjective visual comparison of experimental and calculated images. For example, air-sulfur hexafluoride boundaries can be analyzed with fractal-dimension analysis, which quantifies the complexity of this interface. Another useful technique is the separation of the deterministic (predictable) flow from the stochastic (variable) portion of the flow, which can be predicted only statistically. This decomposition of shock-tube flows into deterministic and stochastic features is possible because the flows are sufficiently reproducible that we can do ensemble-averaging of dozens of data shots. Such decomposition is especially helpful to theorists because the deterministic portion of the flow is susceptible to calculation by Euler equations, whereas the stochastic features require a turbulence model. Wavelet analysis also examines flow morphology. Other physics-based analysis methods are being developed as part of a Laboratory-Directed Research and Development project. These methods are being applied to radiographic data.

One important physics model validation study with

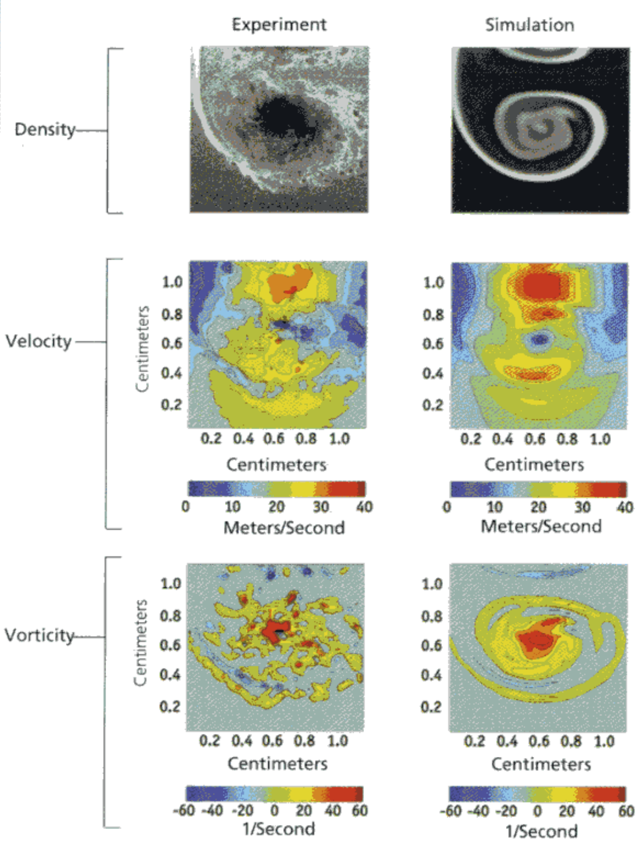

Figure 3. Experimental data are compared with code output by using 2-D density, velocity, and vorticity fields. Large scales (several millimeters) show good agreement but significant differences appear at small scales (submillimeters), where experimental data show more structure than the code results.

the shock-tube preceded the investigations of heavy-gas cylinders. Instead of sulfur hexafluoride cylinders, we used a thin layer of sulfur hexafluoride with corrugations on both up- and downstream sides of the layer. This experimental target, a "gas curtain," evolved into a complex flow (Figure 4). Before the advent of PIV capability, we developed a physical model—the Jacobs model—to describe the growth rate of this pattern. Flow "circulation," a measure of swirling motion, is the adjustable parameter used to fit the Jacobs model to experimental data. Measuring the circulation with PIV showed excellent agreement with values estimated from the Jacobs model, thereby producing a showcase example of model validation.

Scaling and Uncertainty Quantification

Obviously, the parameters of a shock-tube validation experiment are far from those of a nuclear detonation test, which is prohibited by international treaty. However, our fluid-instability experiments are designed to address only the fluid dynamics of simulation codes for which the relevant scaling parameter is the Reynolds number, the ratio of inertial to viscous forces. Because the Reynolds number in experiments is well above laminar-to-turbulence transition, the experiments can be used to validate codes that calculate this transition in highly distorted flows driven by shock waves.

Shock-tube experiments do address the current emphasis on uncertainty quantification. Because

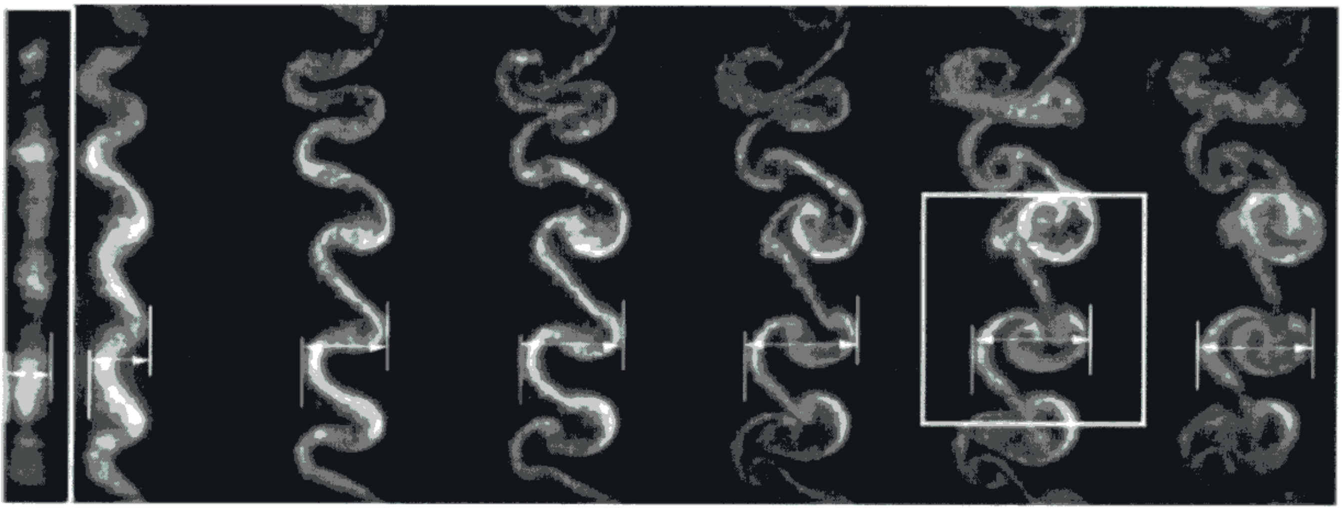

Figure 4. Series of experimental images of the cross section of a heavy-gas flow driven by a shock wave (i.e., gas-curtain experiment) showing how the swirling motion becomes highly distorted just before it becomes turbulent.

fluid instability is highly nonlinear and because we perform hundreds of experiments with nearly identical initial conditions, we produce large quantities of data by applying ensemble-averaging and statistical analyses to determine the variability of important quantities and the sensitivity of one variable to another. These data enable precise determination of error and uncertainty, unlike most integrated experiments (that utilize only one or a few shots) that rely on calculations to assess uncertainty. Thus, simulations of these validation experiments can assess code uncertainties—another benefit of validation exercises.

Uncertainty quantification is especially important for phenomena that are highly nonlinear, including much of the physics of a nuclear weapon. Thus, effective validation science must include experimental data for which subtle changes in initial experiment conditions produce profound changes in observable phenomena. Ultimately, we are concerned about subtle changes in the initial state of a weapon that could lead to significant changes that could lead to nuclear detonation. An example of phenomena with high sensitivity to initial conditions is a "bifurcated flow," in which distinctly different flow patterns are observed when initial conditions change microscopically.

This phenomenon of flow bifurcation is clearly evident in the simultaneous acceleration of three heavy-gas cylinders by a planar shock wave. Typical data in four experiments with the same nominal initial conditions show markedly different flow features (Figure 5). Computer simulations have calculated one of these four patterns, and work is ongoing to learn which subtle initial differences can lead to large differences in postshock flow. As researchers learn how to simulate the other three flow patterns, they will have increased confidence in their fluid dynamic algorithms. This work will lead to greater awareness of code uncertainties, which they will quantify. Thus, this experiment not only challenges the hydrocodes but leads to increased confidence in code credibility and in quantitative understanding of code uncertainty.

Figure 5. Flow bifurcation. Each pair of images shows the flow evolution of three heavy-gas cylinders that are accelerated simultaneously by a planar shock wave. Each of the four image-pairs shows flow during an experiment that has nearly the same initial conditions as the others. The strikingly different shapes of the flows demonstrate the extreme sensitivity of the flow on initial configuration. This sensitivity and strong nonlinearity produces a flow bifurcation that constitutes an outstanding code validation experiment.

Identifying strong nonlinear phenomena and quantifying uncertainty have other important benefits for the weapons program. The researcher performing the calculations—whether designer, code developer, or analyst—will be calibrating his or her judgment about nonlinear fluid dynamics and about the code itself. Thus, a validation exercise that has challenging data like the triple-cylinder experiment validates both the code and the researcher, who learns the code's capabilities and limitations in addition to learning the physics of the experiment. Therefore, validation science is the cornerstone of predictive capability.

Detonation Shock Dynamics Experiment

We can conduct yet another type of validation experiment in support of the detonation shock dynamics (DSD) model. DSD is an approximation to the reactive Euler equations that allows computationally efficient tracking of curved detonation waves. DSD bypasses poorly known attributes, such as equation of state for the reacting explosive mixture and the reaction rate law, in favor of a direct experimental calibration. The resulting mathematical function describes the relatively simple net effect propagation of many complex processes on the detonation shock.

The classic experiment in these studies is the rate stick, a long cylinder of high explosive that is initiated at one end. Measuring the detonation velocity through the charge and observing the detonation as it emerges from the cylinder end, we can reconstruct the curved wave shape in the stick. Ideally this procedure is repeated for a range of charge diameters. Wave shape information for this particular geometry is used to calibrate a propagation law, which the DSD model processes to compute general geometries. These data have validated a DSD model that has been implemented in a programmatically important code at Los Alamos.

Silver Jet Experiment at pRad

A third example of a validation experiment is the silver jet experiment. Driven by high explosives, it creates a metallic (silver) jet and is diagnosed at the proton radiographic (pRad) facility. Code predictions about the shape of a 2-D, blade-shaped jet of silver showed good agreement with pRad images. However, the code also was tested by applying PIV analysis to the pRad images, interpreting persistent features in the images as tracer particles. This analysis produced velocity-field data even though the experiment was not designed for PIV. The result is in good agreement with velocity profiles in the data and simulation codes. Consequently, we have greater confidence in the code's ability to calculate these flows.

Validation Science

In conclusion, validation science compares data from simulation results with data from low-cost experiments in order to validate models and codes, particularly Advanced Simulation and Computing (ASC) codes. Because validation science strongly impacts the credibility of our codes, it is a growing field. The basis for successful validation science is vigorous collaboration among experimenters, analysts, theorists, and code simulators. It is important to note that the three validation experiments discussed here are only a few of the numerous collaborations that Los Alamos and other researchers are using to support science-based validation of the nation's nuclear stockpile.

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Validation experiments have provided enormous benefits to the Laboratory, both scientifically and in academic interaction. The fluid instability project began by collaborations with Jeff Jacobs (University of Arizona) and his students. Then a series of postdoctoral researchers pushed the frontiers of scientific understanding and diagnostics expertise: John Budzinski, Sanjay Kumar, Mark Marr-Lyon, Kathy Prestridge, Paul Rightley, Chris Tomkins, and Peter Vorobieff. Most of them continued their careers as Laboratory staff. Other Los Alamos collaborators on the fluid instability work have been Matt Briggs, Cherie Goodenough, Jim Kamm, Bill Rider, and Cindy Zoldi. John Bdzil, Tariq Aslam, Larry Hill, and many others conducted detonation shock dynamics research. Eric Ferm and Larry Hull performed the silver jet experiments that were analyzed by Kathy Prestridge.

The contributions of many national laboratory and university researchers have promoted a strong culture of science-based prediction at Los Alamos, helping initiate and sustain our validation experiments and science-based predictions. For example, the structure of validation science has been described well by our SNL/NM colleagues, Tim Trucano and Bill Oberkampf. Jeff Jacobs' (University of Arizona) pioneering work on laminar jets and biacetyl-based PLIF led to early gas-curtain experiments; his theory provided the first test of model validation. The shock-tube team at the University of Wisconsin provided validation data for higher flow speeds, as requested by X-Division researchers. The contributions of the University of New Mexico's Peter Vorobieff have been invaluable in conducting experiments and developing innovative approaches to data analysis.